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TECHNICAL NOTE

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TRANSITION REYNOLDS NUMBERS OF SEPARATED FLOWS AT SUPERSONIC SPEEDS

By Howard K. Larson and Stephen J. Keating, Jr.

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Moffett Field, Calif.

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SUMMARY

Experimental research has been conducted on the effects of wall cooling, Mach number, and unit Reynolds number on the transition Reynolds number of cylindrical separated boundary layers on an ogive-cylinder model. Results were obtained from pressure and temperature measurements and shadowgraph observations. The maximum scope of measurements encompassed Mach numbers between 2.06 and 4.24, Reynolds numbers (based on length of separation) between 60,000 and 400,000, and ratios of wall temperature to adiabatic wall temperature between 0.35 and 1.0. Within the range of the present tests, the transition Reynolds number was observed to decrease with increasing wall cooling, increase with increasing Mach number, and increase with increasing unit Reynolds number. The wall-cooling effect was found to be four times as great when the attached boundary layer upstream of separation was cooled in conjunction with cooling of the separated boundary layer as when only the separated boundary layer was cooled. Wall cooling of both the attached and separated flow regions also caused, in some cases, reattachment in the otherwise separated region. Cavity resonance present in the separated region for some model configurations was accompanied by a large decrease in transition Reynolds number at the lower test Mach numbers.

INTRODUCTION

Previous wind-tunnel investigations have disclosed a strong influence of Mach number on the stability of separated laminar boundary layers. Reference 1 points out that as Mach number increases to 4 and higher, the transition Reynolds number of a separated laminar boundary layer approaches that of an attached laminar boundary layer at the same Mach number. In view of their increased stability, separated laminar boundary layers are of practical interest because of the possible unfavorable effects of flow separation on surfaces designed for attached flow and also because of possible favorable effects on heat transfer (ref. 2).

In most practical cases, the aerodynamic heat transfer at high Mach numbers is from the gas to the surface. Experimental results currently available (refs. 3, 4, and 5) show that wall cooling influences the transition characteristics of attached boundary layers; thus an investigation was undertaken to obtain information on the effects of wall cooling on separated boundary-layer transition for a range of supersonic Mach numbers. Since unit Reynolds number also influences transition (refs. 1 and 6), its effects were considered in this investigation.

NOTATION

c_p specific heat at constant pressure, Btu/lb $^{\circ}$R

g acceleration of gravity, ft/sec^2

$\bar{h}$ average heat-transfer coefficient, $\dfrac{\bar{q}}{T_w - T_{aw}}$, Btu/sec ft^2 $^{\circ}$R A178

h depth of separated region, ft

l streamwise length of separated region, ft

L axial or longitudinal distance from origin to reattachment, ft

M Mach number

p static pressure, lb/ft^2

$\bar{q}$ average heat-transfer rate, based on separated or attached boundary-layer area, Btu/sec ft^2

R/ft unit Reynolds number at outer edge of separated boundary layer, $\dfrac{\rho_e u_e}{\mu_e}$, ft^{-1}

R_∞/ft free-stream unit Reynolds number, $\dfrac{\rho_\infty u_\infty}{\mu_\infty}$, ft^{-1}

R_{tr} transition Reynolds number, $\dfrac{\rho_e u_e l}{\mu_e}$, for separated flow; $\dfrac{\rho_e u_e x}{\mu_e}$, for attached flow

R_L Reynolds number based on distance L and boundary-layer-edge conditions, $\dfrac{\rho_e u_e L}{\mu_e}$

$\overline{St}$ average Stanton number, $\dfrac{\bar{h}}{\rho_e u_e c_p g}$

T absolute temperature, $^{\circ}$R

u velocity, ft/sec

x streamwise distance along model from leading edge to beginning of transition, ft

μ viscosity coefficient, lb sec/ft^2

ρ mass density, lb sec^2/ft^4

Subscripts

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a adiabatic

e outer edge of separated or attached boundary layer

∞ free-stream conditions

w wall

r reattachment

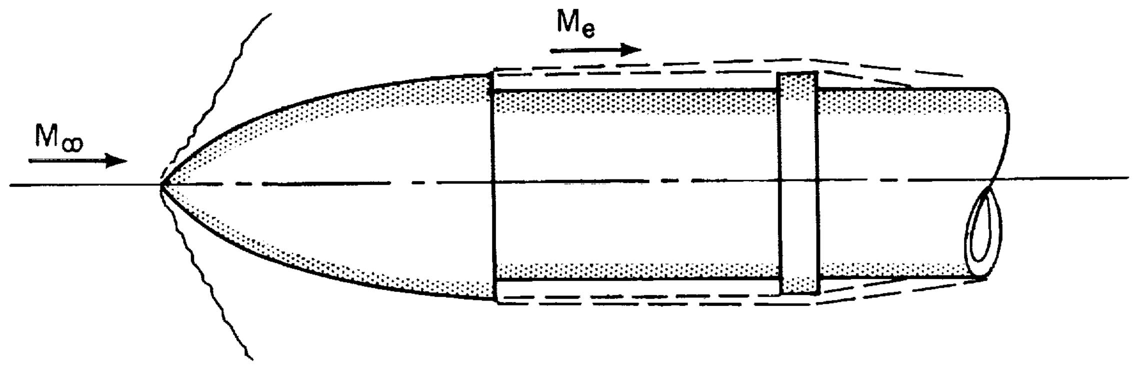
APPARATUS

Wind Tunnel

Tests were conducted in the 1- by 3-foot supersonic wind tunnel no. 1 of the Ames Research Center. This wind tunnel is of the closed-circuit, continuous-operation type and is equipped with a flexible-plate nozzle that permits the Mach number to be set at any value from 1.4 to 4.4. Total pressure can be varied over a maximum range from 1.5 to 60 pounds per square inch absolute but the actual range available varies with the test Mach number.

Models

The axisymmetric model used for obtaining the transition data is shown in figure 1. The ogive nose and sliding ring had the same maximum diameter, which was larger than that of the cylinder, and provided a cylindrical, separated flow as depicted in the sketch below. The length of the separated flow, l, could be varied by moving the sliding ring along the cylinder and locking it in place with a set screw. The depth of the separated region, h, could be decreased by installing concentric sleeves of various lengths and wall thicknesses over the cylinder between the base of the nose and the sliding ring. (The 4° flare just upstream of the exhaust ports was of no consequence in the present investigation.)



The thick copper wall of the model provided an essentially isothermal wall regardless of average wall temperature. The wall temperature could be lowered by spraying liquid nitrogen onto the interior model surfaces. The 1/4-inch-diameter spray tube, mounted concentrically within the model, distributed the spray longitudinally and the nitrogen was eventually discharged to the wind-tunnel stream through the adjustable exhaust ports at the rear of the model. The nose shown in figure 1 was in excellent thermal contact with the rest of the model, and was sprayed with the liquid nitrogen; it will be referred to as the "cooled nose."

An alternate nose of the same external dimensions was also used in some of the tests in order to provide an adiabatic boundary layer for separation over cooled walls. This alternate nose was thermally insulated from the rest of the model, shielded from the nitrogen spray, and will be referred to as the "adiabatic nose."

Instrumentation

Model instrumentation consisted of copper-constantan thermocouples, located approximately as shown in figure 1, and a pressure orifice on the upstream face of the sliding ring, located midway between its inner and outer diameters. The pressure measured with this orifice is designated "reattachment pressure," p_r. Pressure data were obtained on a manometer board in which silicone oil (Dow Corning DC-200-10) was used as the indicating fluid. Copper tubing was used for connecting lines to avoid errors, such as those caused by porosity and outgassing, commonly encountered when plastic or rubber tubing is used at pressures below about 0.4 psia.

Temperatures at the copper-constantan thermocouples were measured by a modified Brown Temperature Indicator which was calibrated for a range of from -326° to -46° F.

Spark shadowgraphs of approximately 0.2 microsecond exposure were recorded on photographic film. Reference 7 contains a description of a spark-shadowgraph system similar in most details to the one used for the present investigation.

DETERMINATION OF TRANSITION

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The general method used for the determination of transition Reynolds number is based on the manner in which the static pressure near reattachment varies with increasing Reynolds number as transition enters the reattachment region. Therefore the transition Reynolds number reported herein is equivalent to the maximum Reynolds number for which laminar flow existed throughout the separated region. It was shown in reference 1 that when transition is downstream of reattachment, the reattachment pressure changes little with increasing Reynolds number, whereas, when transition is just upstream of reattachment, the pressure rises rapidly with increasing Reynolds number. (See figs. 20(a) and (b) of ref. 1 for model S-1.) In the investigations reported in reference 1, transition location was determined from shadowgraphs of the separated boundary-layer flow. With the correlation established between the transition location and reattachment pressure, the shadowgraph technique was abandoned in favor of the more rapid pressure-measuring technique.

Before complete reliance was placed on the correlation shown in reference 1 between the reattachment pressure variation and the onset of transition at reattachment, a brief investigation of this matter was made for the present models. A typical variation of reattachment pressure with Reynolds number (i.e., p_r/p_∞ versus R_∞/ft) for adiabatic wall conditions is shown in figure 2 along with spark shadowgraphs obtained concurrently. The results confirm those of reference 1. Further confirmation is provided by some data which are available from an investigation (ref. 2) of heat transfer in regions of cylindrical, separated flow (on a model similar to that of the present investigation) and two-dimensional, separated flow. These data are the variations of reattachment pressure ratio, p_r/p_∞, and average Stanton number, $\overline{St}$, with R_L shown in figure 3. The rate of change of reattachment pressure ratio with increasing R_L was small and negative when the trend of Stanton number with Reynolds number was typical of laminar flows ($\overline{St} \sim R_L^{-1/2}$), and was large and positive when the Stanton number departed from the laminar trend. Shadowgraphs were obtained for the cylindrical separations; the observed transition correlated well with that deduced from the pressure and heat-tranfer results.

As will be noted from the reattachment pressure curves presented in figures 2 and 3, the upward trend in each curve does not occur sharply and thus does not precisely define the transition Reynolds number. This is to be expected because of the inherent unsteady nature of transition. Thus there is a range of Reynolds numbers for separated boundary-layer transition that corresponds to the "range of transition" observed for attached flows (see refs. 6 and 8). The definition of transition Reynolds number must, therefore, be somewhat arbitrary; but, in keeping with the suggestion in reference 6, it should be "systematic and consistent with the type of observation used for detecting transition." In the present case, transition Reynolds number was defined to be the Reynolds number at which each curve of p_r/p_∞ versus R_∞/ft was intersected by a line drawn parallel to and slightly above the laminar portion of the curve, as shown in figure 2.

Since comparisons of boundary-layer phenomena should be made at corresponding boundary-layer edge conditions, the transition Reynolds number has been calculated using the corresponding Reynolds number per unit length at the edge of the separated boundary layer and the length of separation, $R_{tr} \equiv \rho_e u_e l/\mu_e$.

TEST PROCEDURES

Adiabatic-Wall Data

The following test procedure was used for the adiabatic-wall case. For a given model configuration and test Mach number, the stream Reynolds number was varied by increasing or decreasing the stream stagnation pressure; at each stagnation pressure level, after pressure and temperature equilibrium had been attained, pressure and temperature measurements and shadowgraphs were obtained.

Cooled-Wall Data

It was found necessary to use a different test procedure from that used for the adiabatic-wall case because of extreme difficulty in maintaining a constant value of T_w/T_{aw} as the stream Reynolds number was varied. The following test procedure was found to be suitable for the cooled-wall case. Mach number and Reynolds number were held constant while the model was cooled to the lowest possible temperature (approximately -340° F) and then, as the model was allowed to warm up, concurrent temperature and pressure measurements, and shadowgraphs were obtained. From these measurements, plots were first made of p_r/p_∞ versus T_w/T_{aw} for constant R_∞/ft and M_∞ and these plots were then cross-plotted to obtain the desired plots of p_r/p_∞ versus R_∞/ft at constant T_w/T_{aw} and M_∞. Typical basic plots of p_r/p_∞ versus T_w/T_{aw} are presented in figure 4 along with some of the corresponding shadowgraphs; results of repeating a warm-up run indicated that the data repeatability was good. Crossplots, p_r/p_∞ versus R_∞/ft at constant values of T_w/T_{aw} and M_∞, are shown in figure 5 for $M_\infty = 3.50$; also shown are shadowgraphs obtained at $M_\infty = 3.50$ for $T_w/T_{aw} \approx 0.8$. Two checks were made to test the validity of the procedure used for the cooled-wall case: (1) At $M_\infty = 3.50$ the value of T_w/T_{aw} was held, with difficulty, at 0.70 as the unit Reynolds number was varied and data were recorded in the same manner as for the adiabatic-wall tests. The resulting plot of p_r/p_∞ versus R_∞/ft was compared with that obtained by the cooled-wall method described above and good agreement was found. (2) The plots of p_r/p_∞ versus T_w/T_{aw} were extrapolated to $T_w/T_{aw} = 1.0$ and the resulting plots of p_r/p_∞ versus R_∞/ft were compared with corresponding plots obtained using the direct adiabatic-wall procedure described earlier. Again good agreement was found and the cooled-wall method used was thus considered satisfactory.

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RESULTS AND DISCUSSION

Preliminary Considerations

The transition Reynolds number data were obtained under conditions of varying wind-tunnel stagnation pressure and therefore varying stream unit Reynolds number. Since transition Reynolds number can be affected by varying R/ft, it was considered necessary to determine the effect of R/ft on R_{tr}. This was done for the case of adiabatic walls and the measured effect of R/ft on R_{tr} was found to be small compared to the effects of Mach number and wall cooling. In view of this result, it was believed unnecessary to determine extensively the effect of R/ft on R_{tr} for the case of cooled walls, and the one cooled-wall determination that was made justified this belief.

In determining the effect of unit Reynolds number on transition Reynolds number it was necessary to vary the length of separation. This, however, introduced additional variables, since changing the length of separation changed the following: (1) boundary-layer thickness at separation relative to the length of separation: (2) ratio of separated to attached flow lengths; and (3) geometry of the separated region. Although (1) and (2) varied considerably during the tests, close examination of the present data indicated that, within the range of the variables of this investigation, their effects were small and negligible compared with the effects of Mach number, wall cooling, and unit Reynolds number when transition is based on the length of separation. No attempt was made to account for these two effects when the effects of the major variables were considered. Preliminary tests did show a considerable effect of changing the relative dimensions, or geometry, of the separated region, for example, increasing the depth, h, independent of the length, l.

It was found that for ratios of length to depth, l/h, greater than about 30, the boundary layer tended to reattach upstream of the ring, causing adverse pressure gradients and decreased transition Reynolds numbers. It was also found that at values of l/h less than about 15, a cavity-resonance phenomenon could occur and result in marked decreases in the transition Reynolds number. For example, when the depth was changed so that $l/h = 5$ at $M_e = 2.54$, strong resonance was present and the transition Reynolds number was reduced to one-third the value measured without resonance ($l/h = 20$). It should be noted that the presence and effect of resonance was most apparent at the lower Mach numbers and very slight at $M_e = 4$. The results presented in succeeding sections are for $17.5 < l/h < 24$ since these configurations provided a straight, resonance-free separated flow of essentially constant pressure.

Since the effect of unit Reynolds number, R/ft, on transition Reynolds number is present in most of the data to be presented, data showing the effect of unit Reynolds number will be discussed first. Also, since the effect of R/ft was measured over a range of Mach number, the effect of Mach number independent of unit Reynolds number was determined for the adiabatic-wall case and will be presented next. Finally, data showing the effects of wall cooling but including the effect of R/ft will be presented and compared with other data.

Effect of Unit Reynolds Number

Tests were performed under adiabatic-wall conditions to determine the effect of unit Reynolds number independent of Mach number and vice versa. The tests determined the unit Reynolds number for transition at reattachment over a Mach number range for each of five separation lengths. The resulting data are presented in figure 6 where lines have been faired through the data for each of the separation lengths. The curves of figure 6 were then cross-plotted at $M_e = 2.6$, 3.0, and 3.5 and the resulting unit Reynolds numbers of transition were multiplied by the appropriate separation lengths to obtain transition Reynolds number. The resulting plots of R_{tr} versus R/ft are presented in figure 7 and exhibit a trend of increasing transition Reynolds number with increasing unit Reynolds number. This trend is similar in magnitude and direction to that usually observed for attached boundary-layer transition in wind-tunnel tests.

The cause of this unit Reynolds number effect has been made apparent through studies by Laufer (ref. 9). It is shown in reference 9 that free-stream fluctuations in supersonic wind tunnels result from a sound field that is propagated from the turbulent boundary layer on the wind-tunnel walls. It is also shown in reference 9 that the intensity of the free-stream fluctuations increases with decreasing stream unit Reynolds number. This is a result of the increase in scale of the boundary-layer disturbances with increasing boundary-layer thickness on the wind-tunnel walls which increases with decreasing stream unit Reynolds number. Therefore it is important that transition Reynolds number data or other aerodynamic data that are influenced by transition should be compared with caution when obtained in various facilities or in one facility under varying stagnation pressure or unit Reynolds number.

The effect of unit Reynolds number, described above, causes the measured effects of other independent variables (such as M_e or T_w/T_{aw}) to appear greater than they would be if R/ft were held constant. If on a given model, for example, changing an independent variable results in increased R_{tr}, the higher values of R_{tr} would be obtained at higher values of R/ft which also increases R_{tr} (and vice versa if changing the independent variable causes decreases in R_{tr}).

Effect of Mach Number

The effect of Mach number on transition Reynolds number is presented in figure 8 for constant unit Reynolds number and adiabatic-wall conditions. The curves were obtained by cross-plotting the data of figure 6 for values of R/ft of 1.2 and $2.0{\times}10^6$ and multiplying by the appropriate separation lengths. Large increases in transition Reynolds number with increasing Mach number are evident in the plots of figure 8. This trend observed for the present axially symmetric flows agrees well with the results presented in reference 1 for two-dimensional flows. A comparison of the results will be presented later.

A comparison of the faired curves of figure 6 with the cross plots of figure 8 shows graphically the effect of variable unit Reynolds number described in the previous section. Figure 6 is a plot of R/ft versus M_e and the faired curves are for constant separation lengths. Therefore these curves essentially represent the variation of transition Reynolds number with Mach number for a variable unit Reynolds number. The effect of Mach number appears greater in figure 6 than in figure 8 because of the unit Reynolds number effect. This effect is also present in subsequent plots.

Effect of Wall Cooling

The effect of wall cooling on transition Reynolds number is presented in figure 9. These data were obtained from curves similar to those of figure 5 for one model length at $M_e = 2.60$, 3.49, and 4.24 and two model lengths at $M_e = 2.60$. A consistent trend of decreasing transition Reynolds number with decreasing wall-temperature ratio is evident for each case. It should be noted that for values of T_w/T_{aw} below about 0.6 to 0.7 a coating of frost was present on the cooled portions of the model surface. Since frost represents a form of distributed roughness of undetermined magnitude, it could have influenced transition. The data of figure 9 do not indicate a change of trend or unusual behavior in the vicinity of $T_w/T_{aw} = 0.6$ to 0.7; however, this is not sufficient evidence that frost did not affect transition since other effects could have compensated for its effect. Therefore, no conclusions as to the effects of frost can be based on these data.

It is important to note that the trend of decreasing R_{tr} with decreasing T_w/T_{aw} evident in figure 9 is opposite to that usually observed for moderate cooling of attached boundary layers (refs. 3, 4, 5, and 6). Moderate wall cooling, $T_w/T_{aw} > 0.5$, was observed in the above references to have a considerable stabilizing influence (increasing R_{tr} with decreasing T_w/T_{aw}); whereas extreme wall cooling, below about $T_w/T_{aw} = 0.5$, resulted in marked decreases in transition Reynolds number (transition reversal) with decreasing wall-temperature ratios. In view of this difference in the effect of wall cooling on attached and separated flows, the question arose as to whether the trend observed in figure 9 was the result of cooling the attached boundary layer upstream of separation, the result of wall cooling in the separated region only, or a combined result of cooling both the attached and separated flow regions. In an attempt to shed some light on this question, the effect of cooling only the separated-flow region was investigated. For this purpose the adiabatic nose was used in a series of cooled wall runs at $M_e = 3.49$. The resulting data are presented in figure 10 along with a curve representing the corresponding data obtained for wall cooling of both the nose and separated regions (fairing of $M_e = 3.49$ data of fig. 9). It should be noted that for the adiabatic-nose data of figure 10, the nose surface was frost-free for all values of T_w/T_{aw}; however, frost was still present on the cooled surfaces of the model at values of T_w/T_{aw} below about 0.6 to 0.7. It is evident in figure 11 that cooling the separated region alone resulted in a slight, but measurable, decrease in R_{tr} with decreasing T_w/T_{aw}, that was considerably less than that observed for the case of cooling the wall of both the nose and separated-flow regions.

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Wall cooling of both the nose and separated-flow regions was observed, in some instances, to cause reattachment of the separated boundary layer onto the surface of the smaller diameter cylinder. (See shadowgraph numbers 1 and 2 of fig. 4(a) and number 7 of fig. 5.) The wall temperature ratio at which this reattachment occurred was found to increase with increasing unit Reynolds number and, since reattachment was observed at $T_w/T_{aw} = 0.82$ (shadowgraph number 7 in fig. 5), the presence of frost was not the cause of this phenomenon. During the adiabatic-wall tests, reattachment to the cylindrical surface was not observed even at the highest free-stream unit Reynolds numbers of about $8{\times}10^6$ ft^{-1} (reattachment to the cylinder always occurred at higher unit Reynolds numbers than were required to barely cause transition at the ring and therefore did not affect any of the transition data reported herein.)

Comparison of Present Results With Reference 1

The results obtained in the present investigation for axially symmetric flows are compared in figures 11 and 12 with the results of reference 1 for two-dimensional flows. In figure 11 the effects of unit Reynolds number on transition Reynolds number for both adiabatic- and cooled-wall conditions found in the present tests are compared with results from reference 1 for flat-plate transition under adiabatic-wall conditions; all the data were obtained in the same wind tunnel. The magnitude and trend of the unit Reynolds number effect are similar for the various cases presented. The effect of Mach number on transition Reynolds number for the present test of both adiabatic- and cooled-wall conditions and for two-dimensional separated flows (ref. 1) is presented in figure 12. For consistency, the results of reference 1 have been converted to boundary-layer-edge conditions. The present results for $T_w/T_{aw} = 1.0$ agree well in magnitude and trend with the results of reference 1 which were also for the adiabatic-wall case. The curves representing $T_w/T_{aw} = 0.7$ and 0.4 were obtained by cross-plotting the faired curves in figure 9 for $l = 0.169$ foot. It is readily apparent that the strong effect of Mach number, previously observed for adiabatic flows, also exists for the case of wall cooling, at least within the range of the present tests. It should be noted again, however, that these data are for a range of unit Reynolds numbers and therefore show an apparent stronger effect of Mach number than would be the case if the data were obtained for a constant unit Reynolds number.

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CONCLUSIONS

A wind-tunnel investigation of the effect of wall cooling on the transition Reynolds number of laminar, separated boundary layers was conducted at Mach numbers from 2.06 to 4.24. Cylindrical, separated boundary layers downstream of an ogive nose were studied using pressure measurements and shadowgraphs. From the resulting data, the following conclusions were reached:

1. The transition Reynolds number for separated boundary layers decreased with increasing wall cooling, and in some cases, wall cooling was observed to cause reattachment in an otherwise separated region.

2. Wall cooling of the attached boundary-layer region upstream of separation in conjunction with cooling of the separated region caused approximately four times as great a reduction in transition Reynolds number as cooling the walls of the separated region only.

3. The marked increase in stability of separated, laminar boundary layers with increasing Mach number, reported in reference 1 for the adiabatic-wall case, was also observed over the range of wall cooling of the present tests.

4. The increase in transition Reynolds number with increasing unit Reynolds number was independent of other variables.

5. The variation of the ratio of pressure near reattachment to free-stream static pressure, p_r/p_∞, with free-stream unit Reynolds number, R_∞/ft, provided a good indication of the Reynolds number at which transition entered the reattachment region of a separated, laminar boundary layer. Both shadowgraph observations and heat-transfer measurements correlated well with the abrupt rise in the p_r/p_∞ versus R_∞/ft plot as an indication of the movement of transition upstream into the reattachment region.

6. Resonance in the separated region, observed for certain model configurations, was accompanied by large reductions in transition Reynolds number at the lower test Mach numbers.

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National Aeronautics and Space Administration
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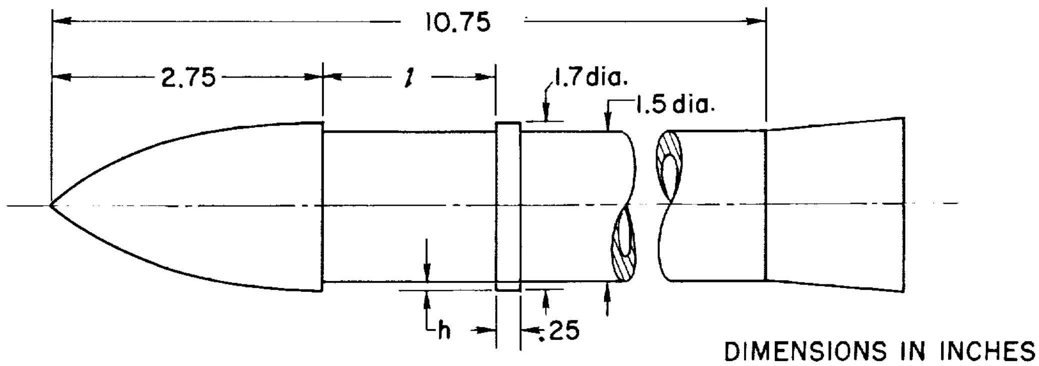

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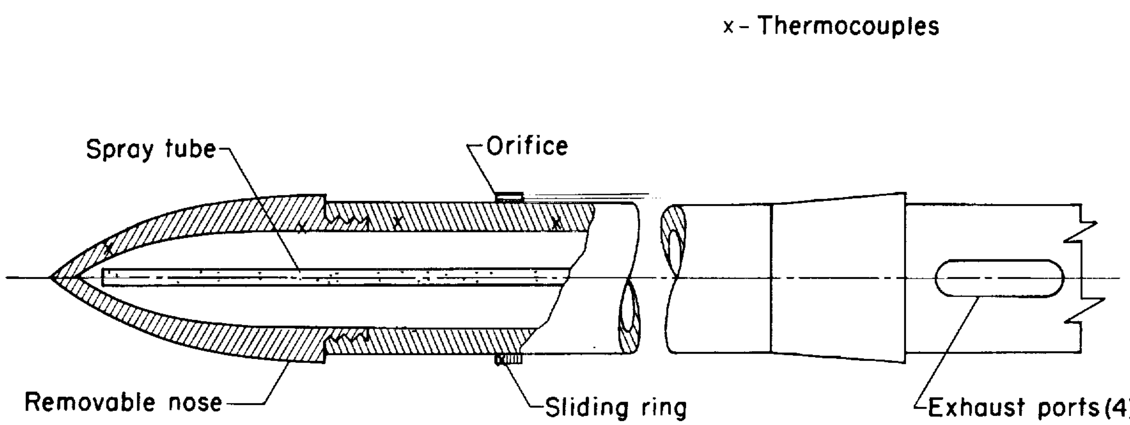
EXTERNAL DETAIL



INTERNAL DETAIL

Figure 1.- Model details.

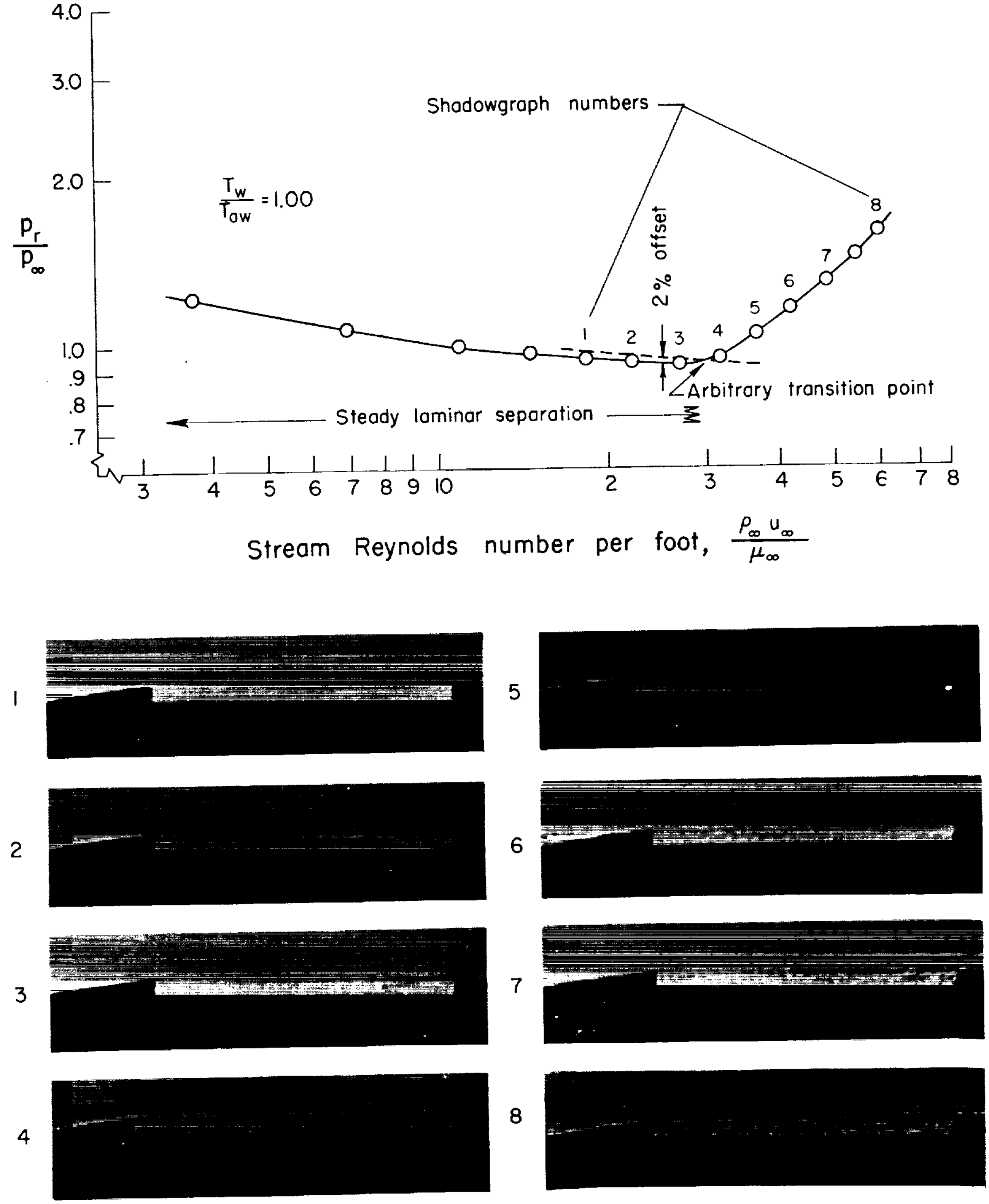


Figure 2.- Variation of reattachment pressure with unit Reynolds number and corresponding shadowgraph observations; $M_\infty = 3.50$.

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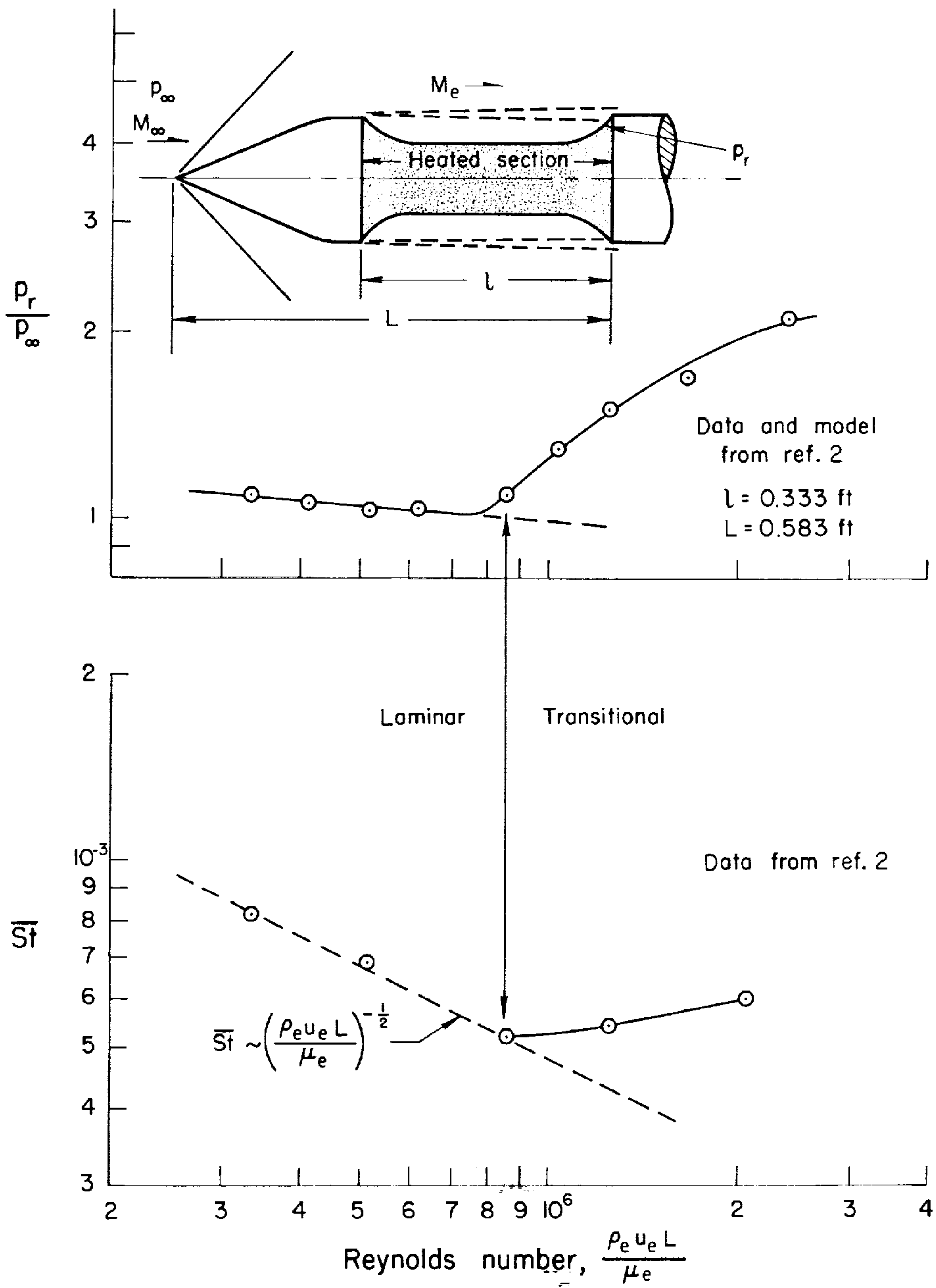
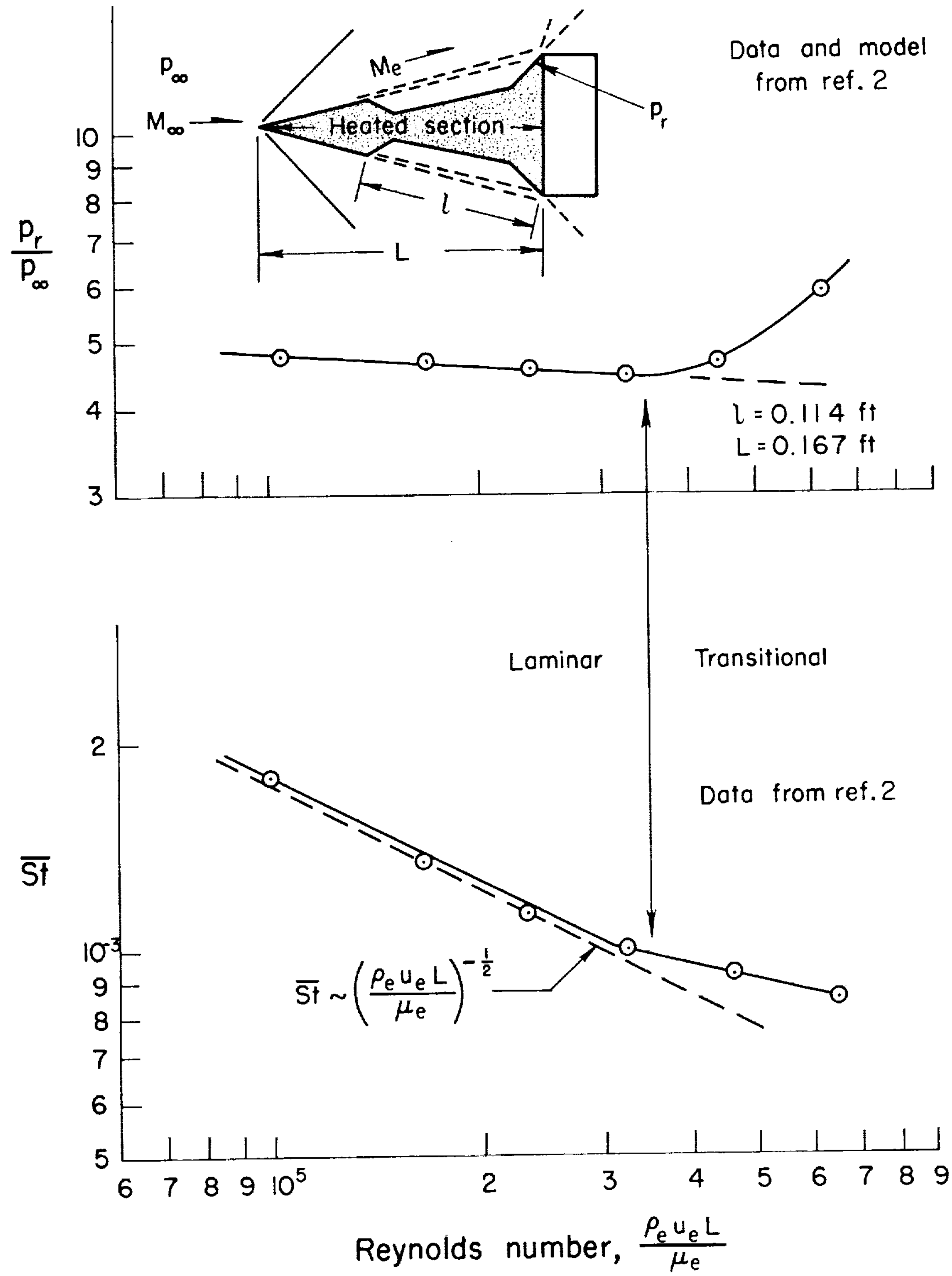


(a) Axially symmetric model, $M_e = 4.0$

Figure 3.- Variation of reattachment pressure with Reynolds number and corresponding heat-transfer measurements.



(b) Two-dimensional flow; $M_e = 3.0$.

Figure 3.- Concluded.

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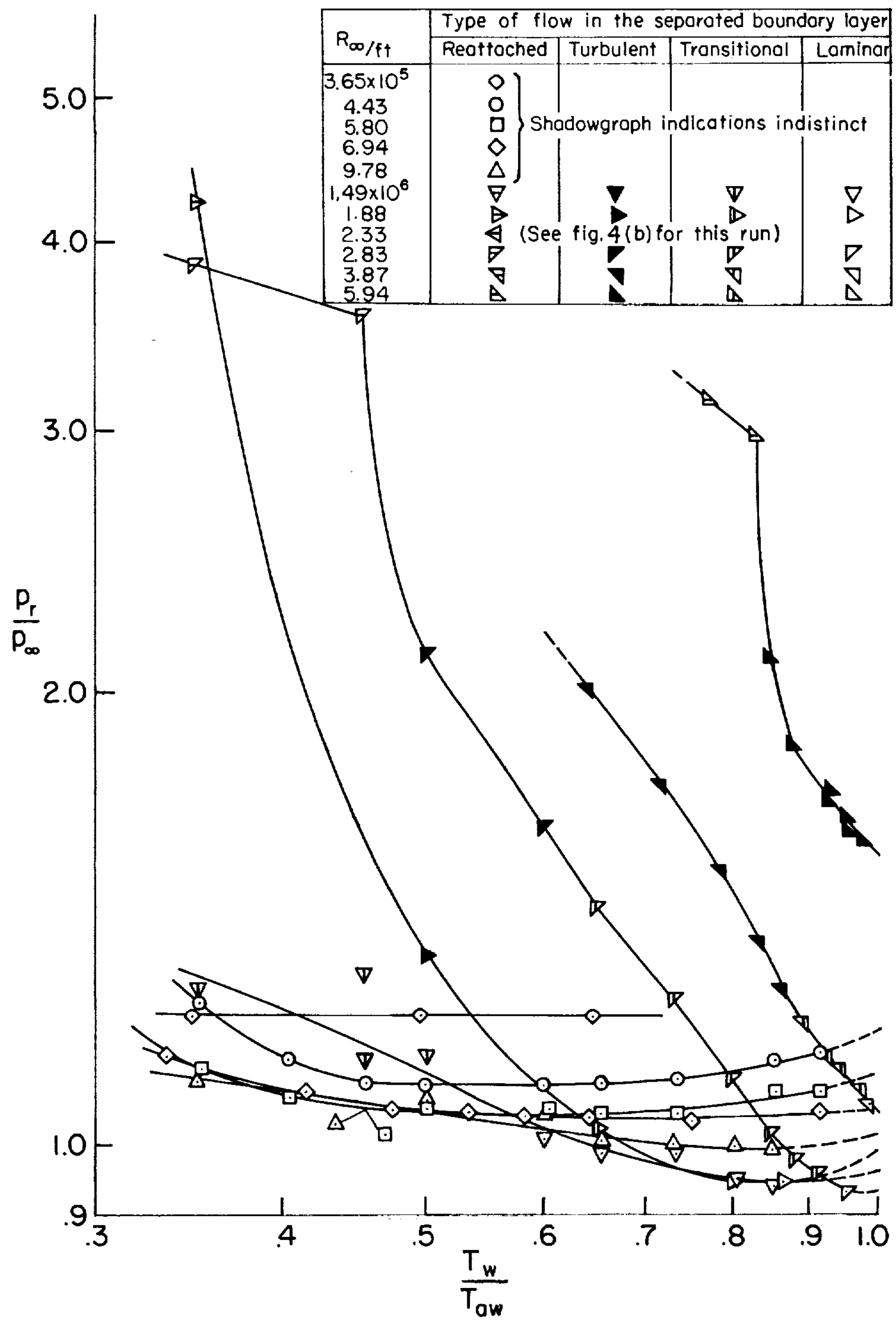
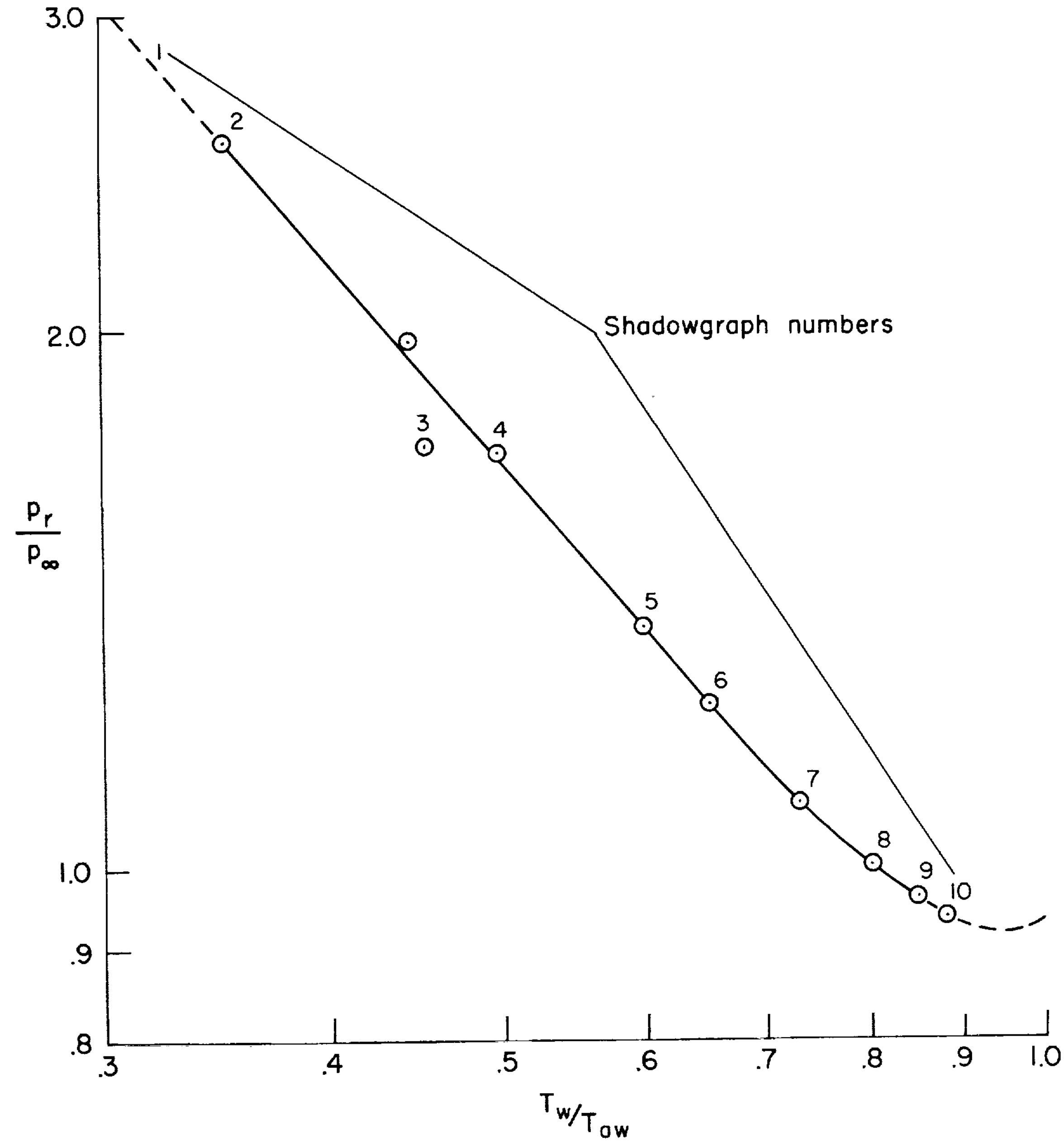


(a) Various values of unit Reynolds number.

Figure 4.- Variation of reattachment pressure with wall temperature for $M_\infty = 3.50$.



(b) $R_\infty/\mathrm{ft} = 2.33\times10^6$

Figure 4.- Continued.

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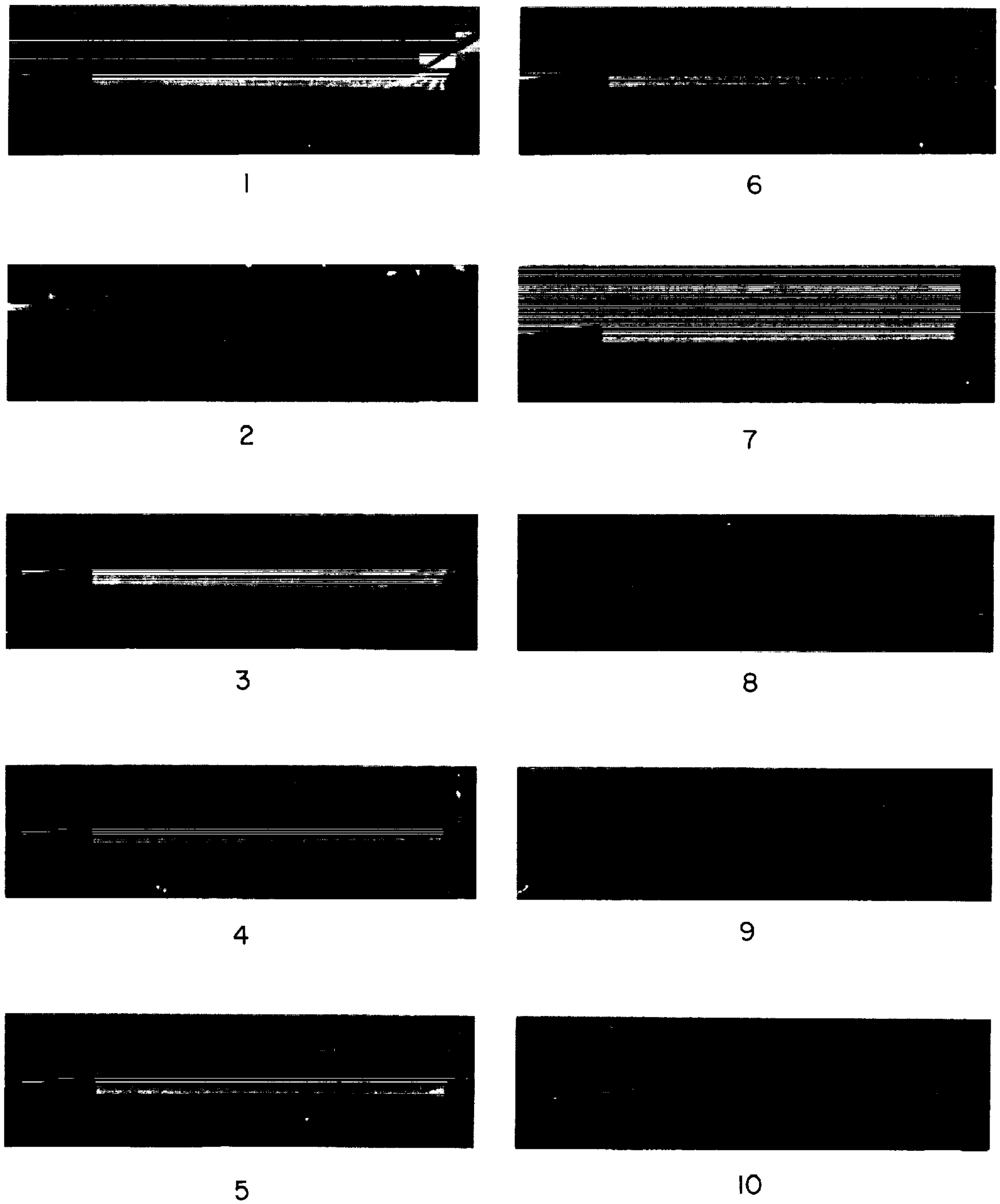
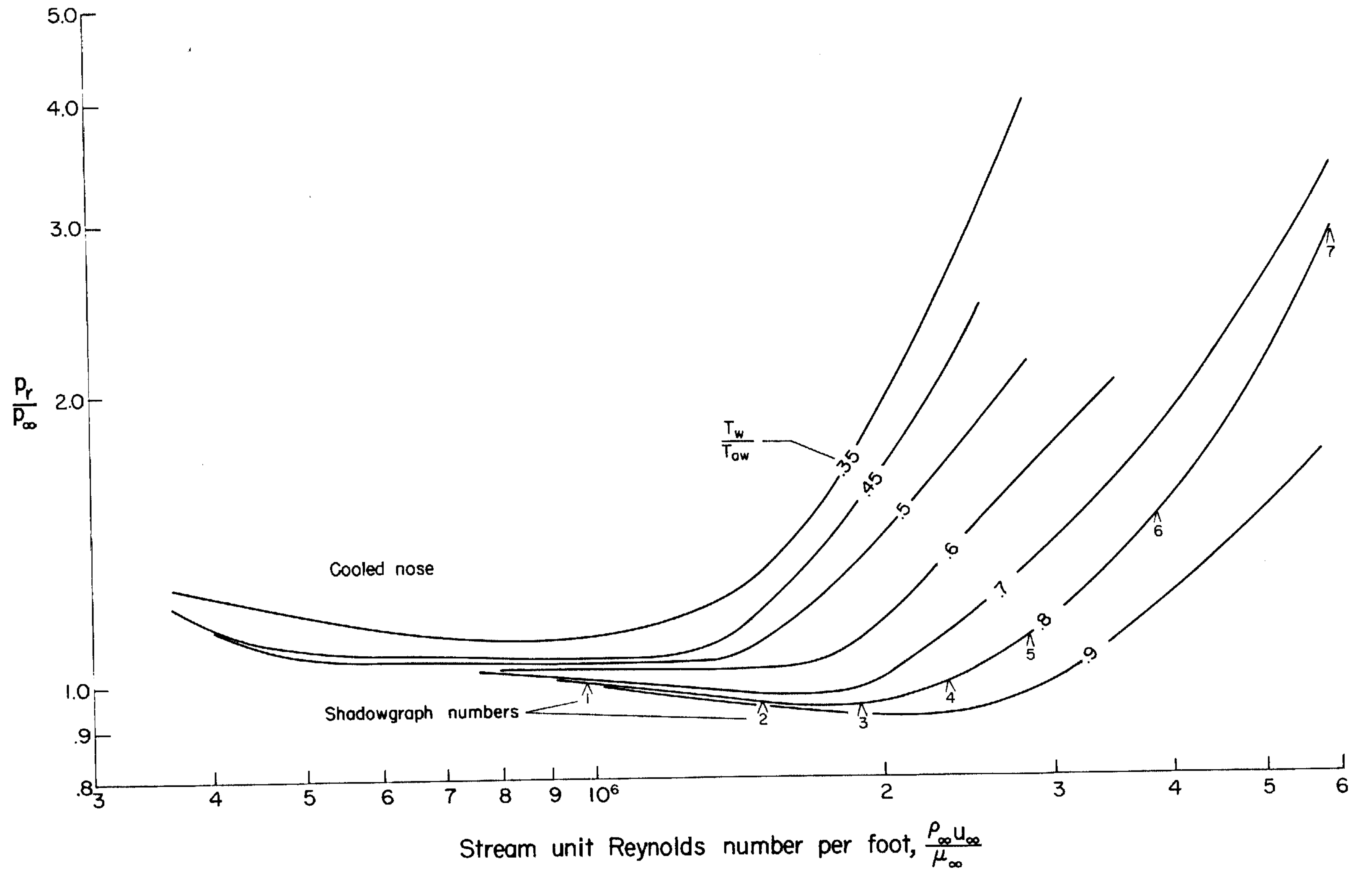


(b) $R_\infty/ft = 2.33\times10^6$ – Concluded.

Figure 4.– Concluded



(a) Reattachment pressures.

Figure 5.- Variation of reattachment pressure with unit Reynolds number for various values of T_w/T_{aw}; $M_\infty = 3.50$ (cross-plotted from fig. 4).

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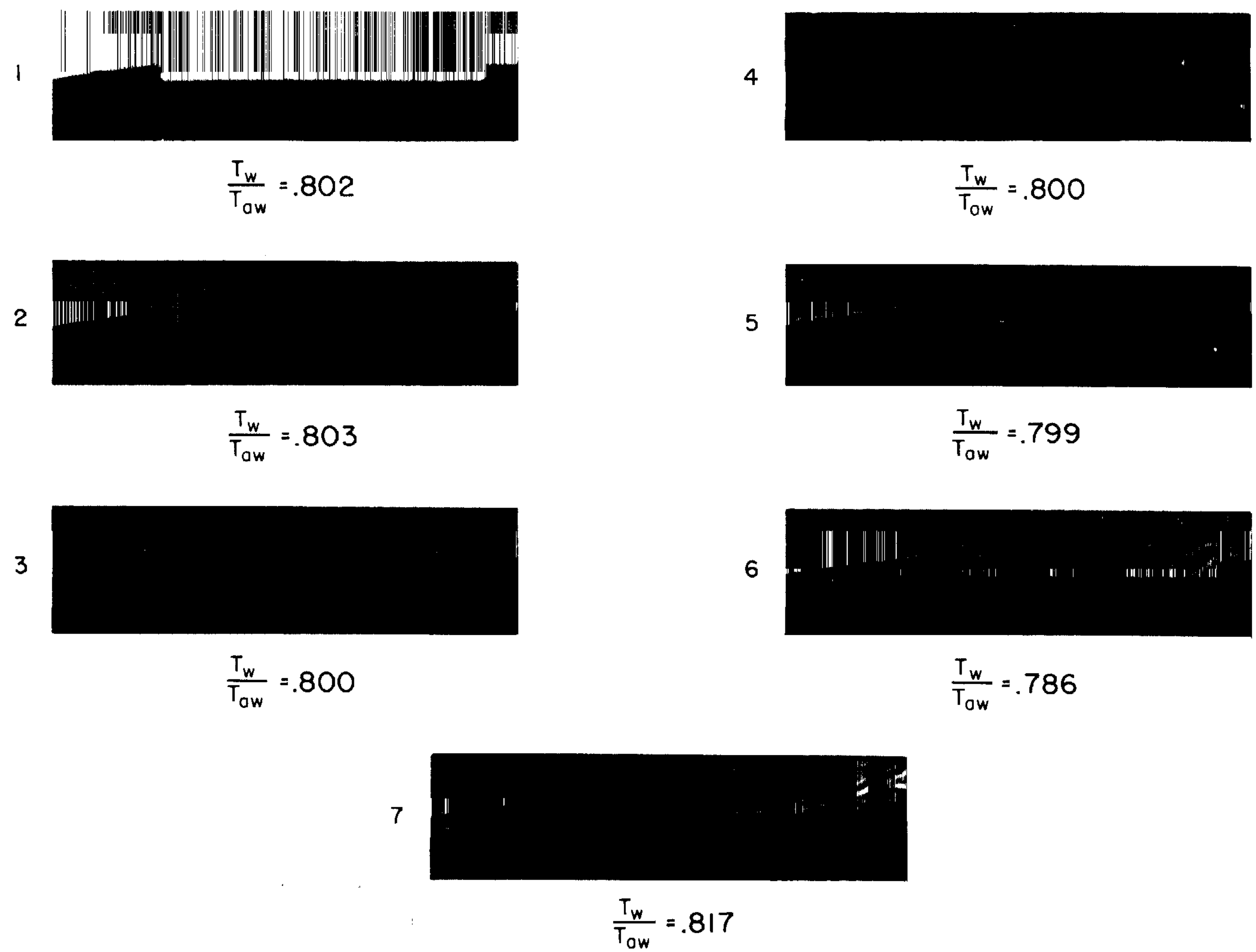

(b) Shadowgraphs for T_w/T_{aw} of approximately 0.8.

Figure 5.- Concluded.

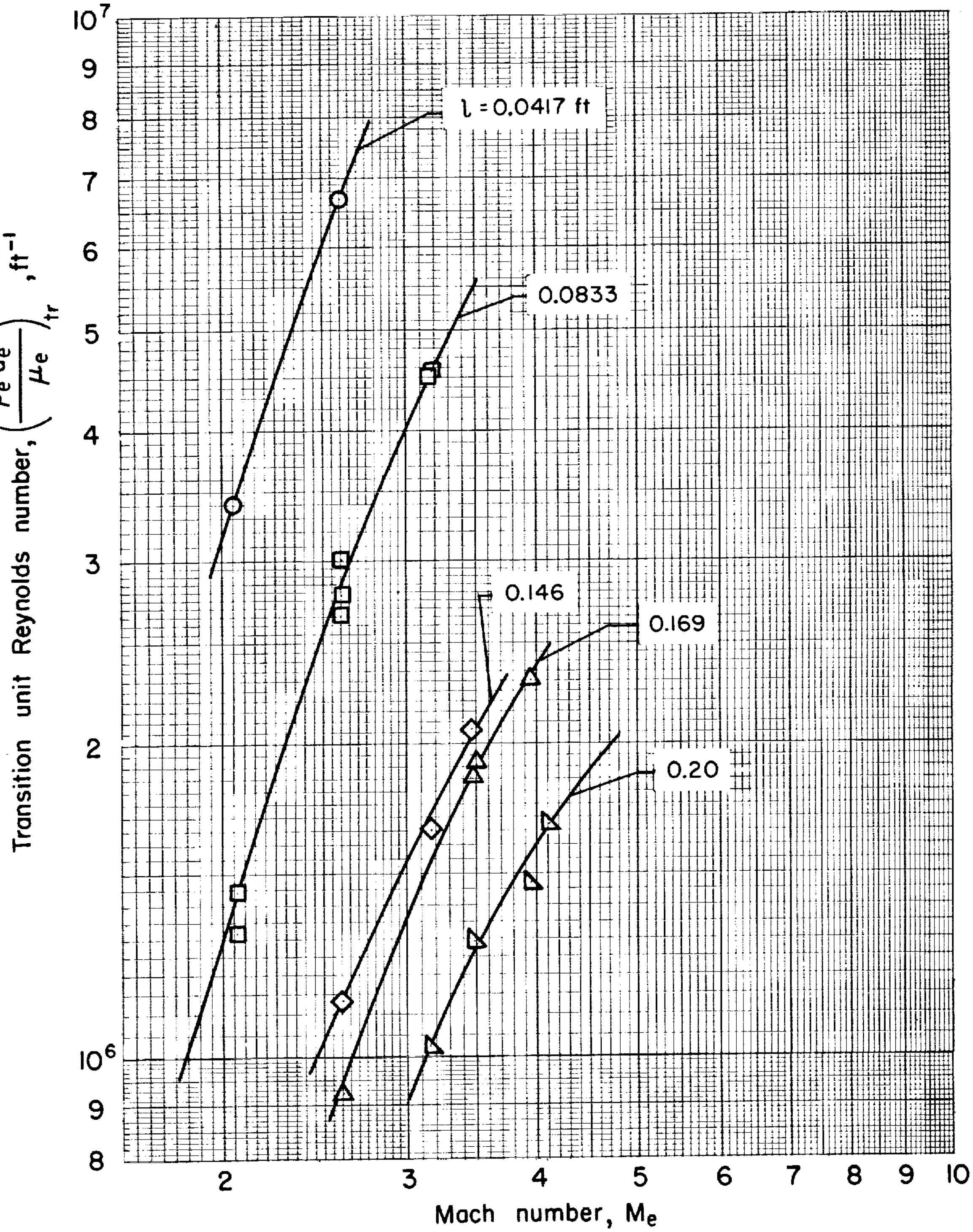

Figure 6.- Variation of unit Reynolds number for transition at reattachment with Mach number for various lengths of separation; $T_w/T_{aw} = 1.0$.

A
1
7
8

A
1
7
8

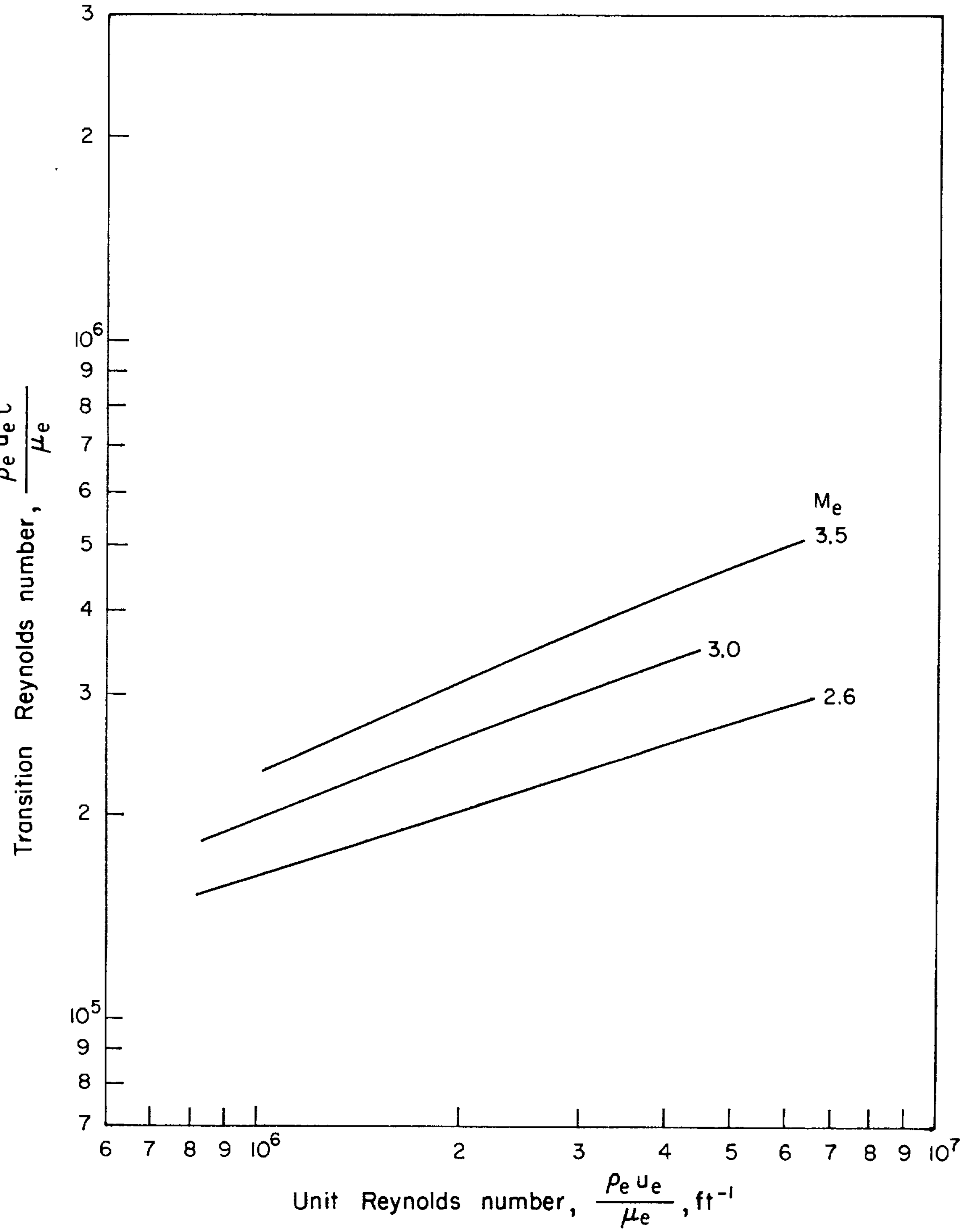

Figure 7.- Variation of transition Reynolds number with unit Reynolds number at M_e = 2.6, 3.0, and 3.5; T_w/T_{aw} = 1.0.

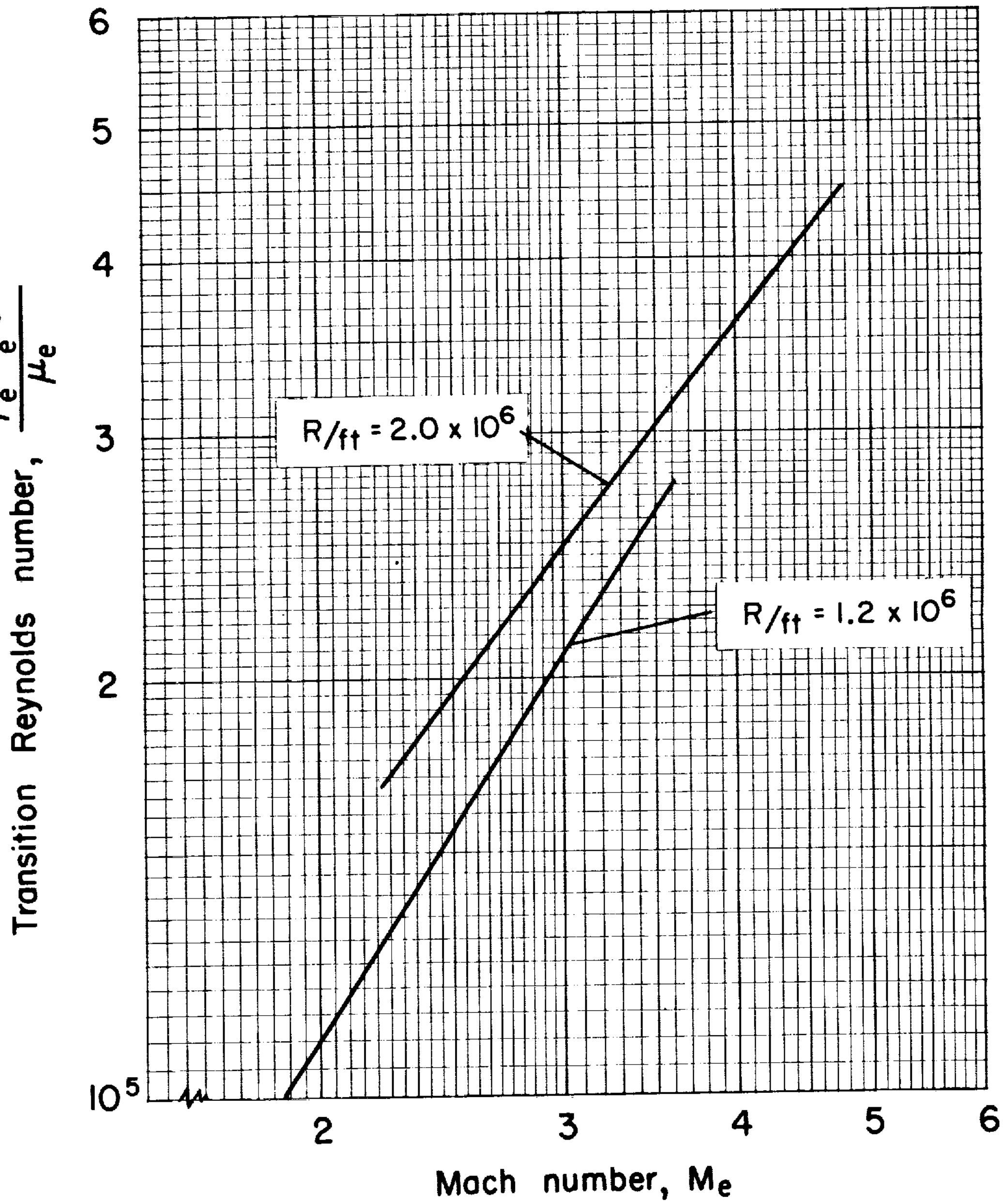

Figure 8.- Variation of transition Reynolds number with Mach number for constant unit Reynolds number; $T_w/T_{aw} = 1.0$.

A
1
7
8

A
1
7
8

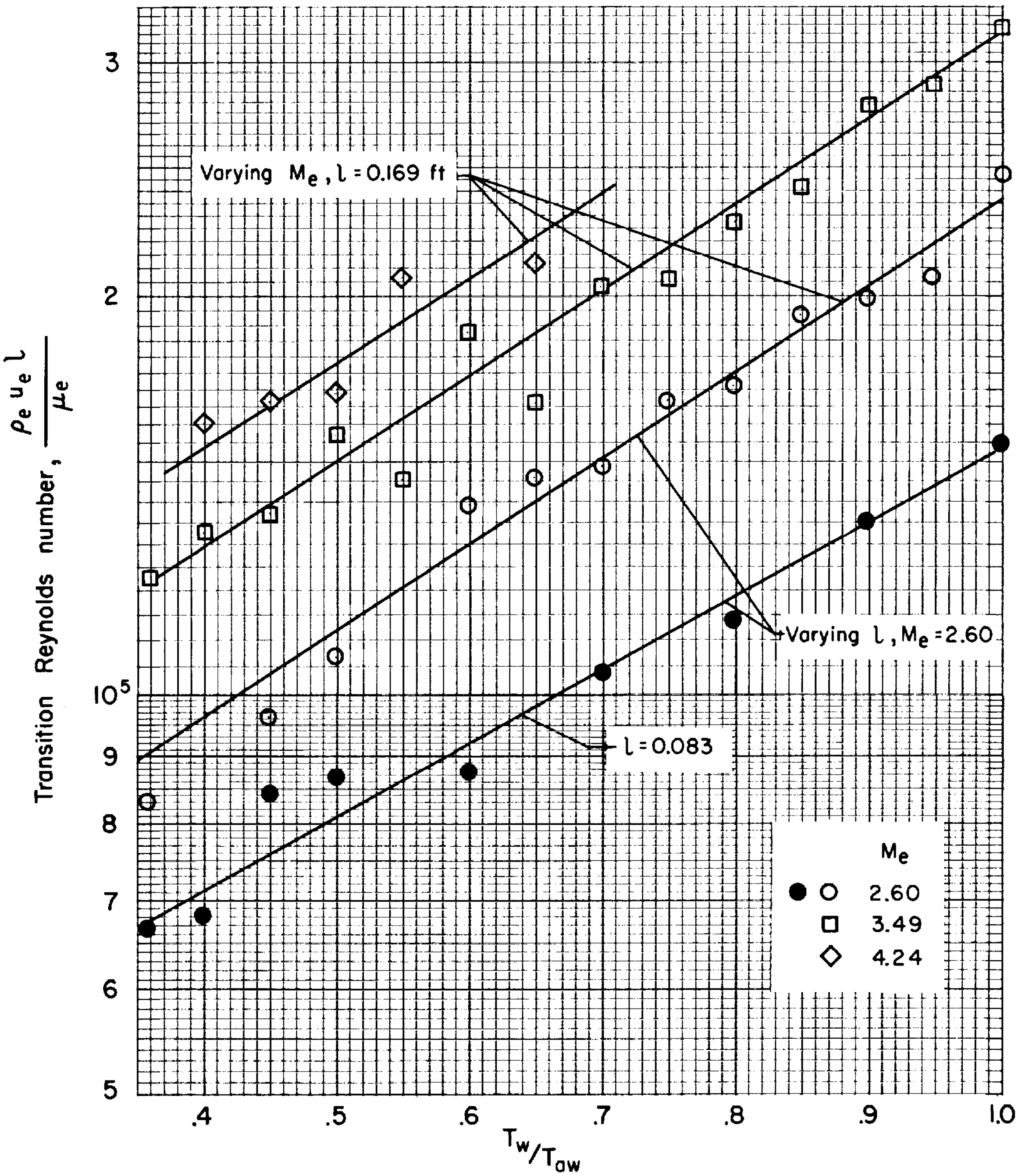

Figure 9.- Variation of transition Reynolds number with wall temperature (cooled nose).

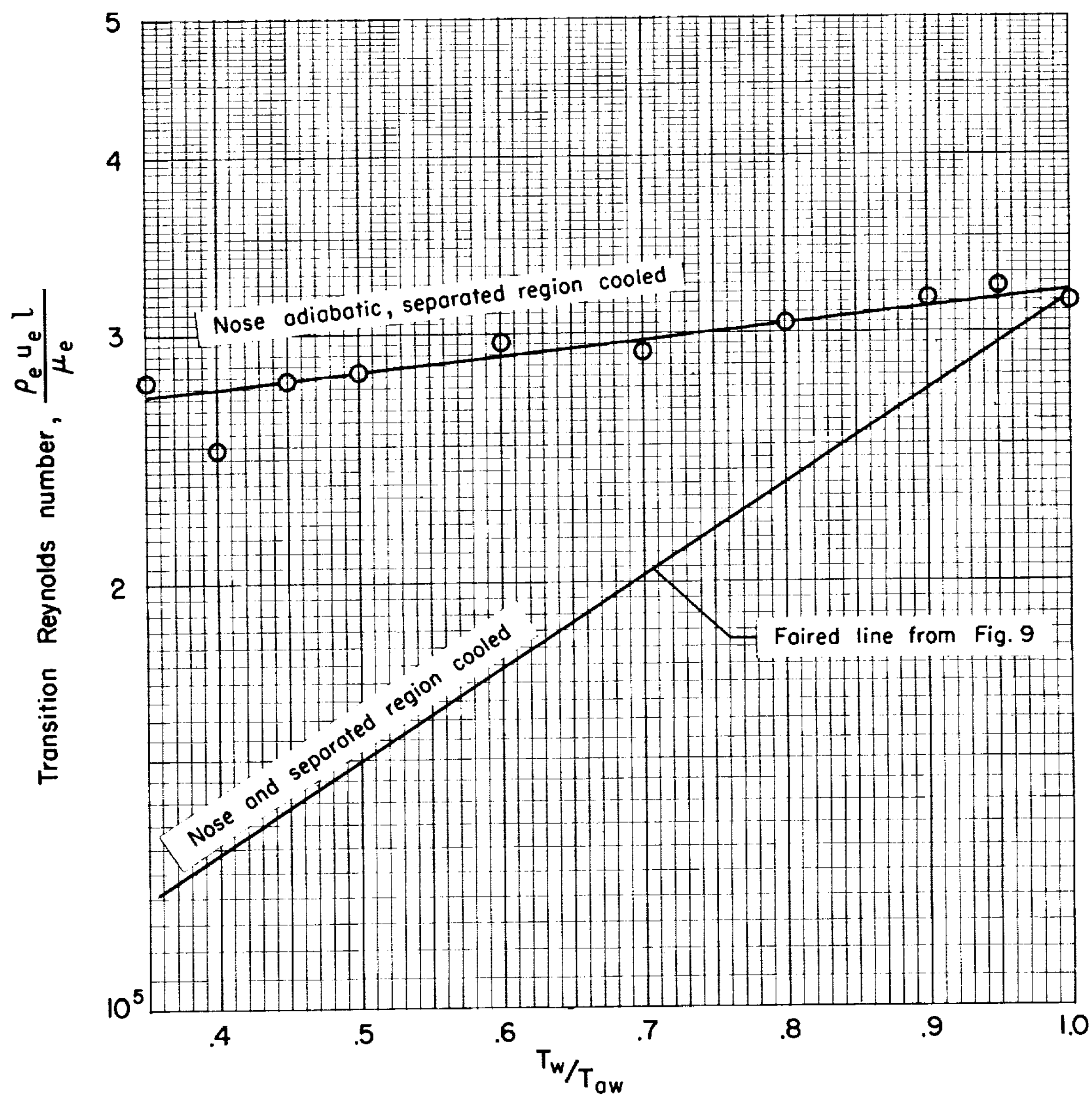

Figure 10.- Variation of transition Reynolds number with wall temperature; $M_e = 3.49$.

A
1
7
8

A
1
7
8

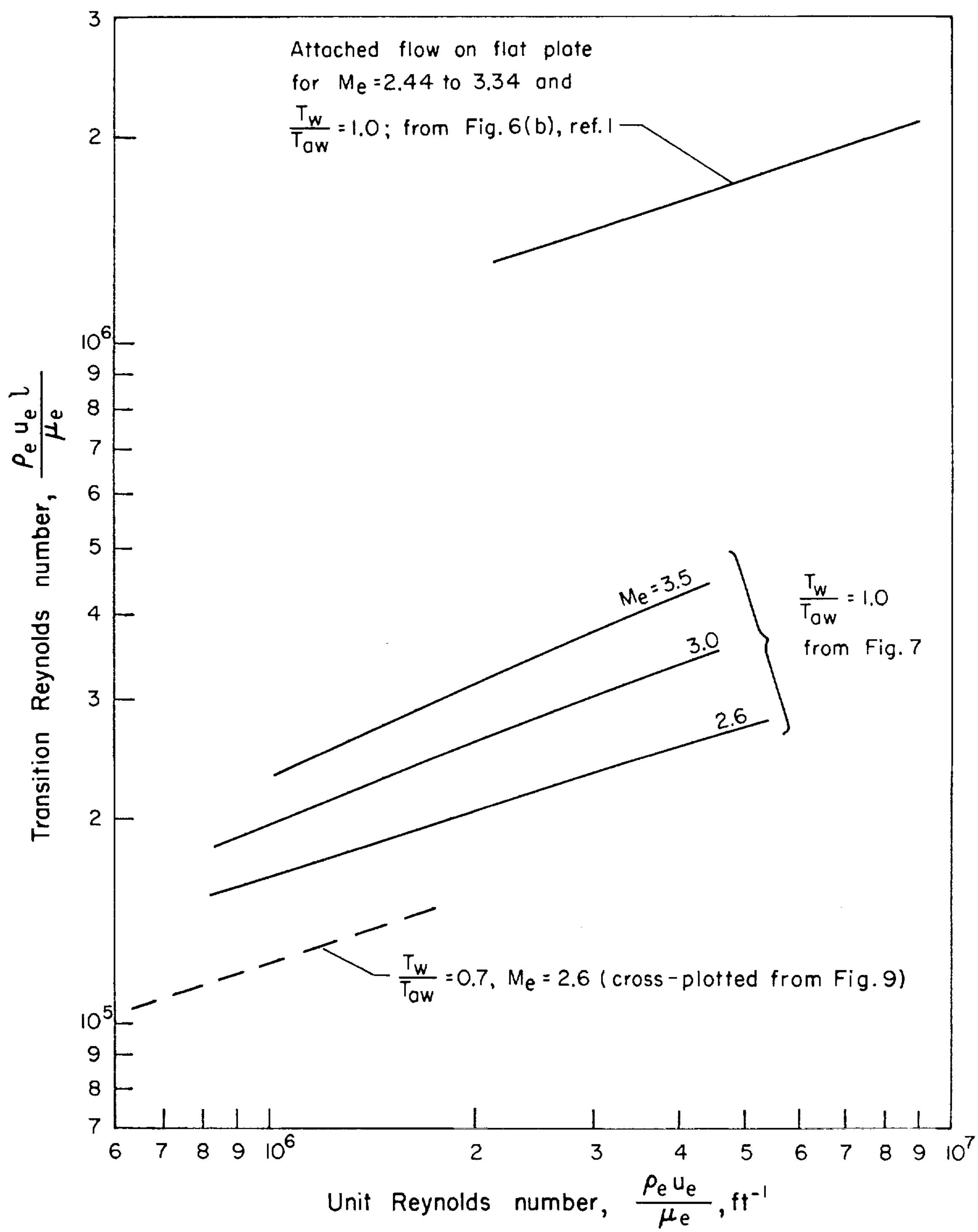

Figure 11.- Comparison of the effect of unit Reynolds number on transition Reynolds number for present separated-flow tests with attached-flow tests of reference 1.

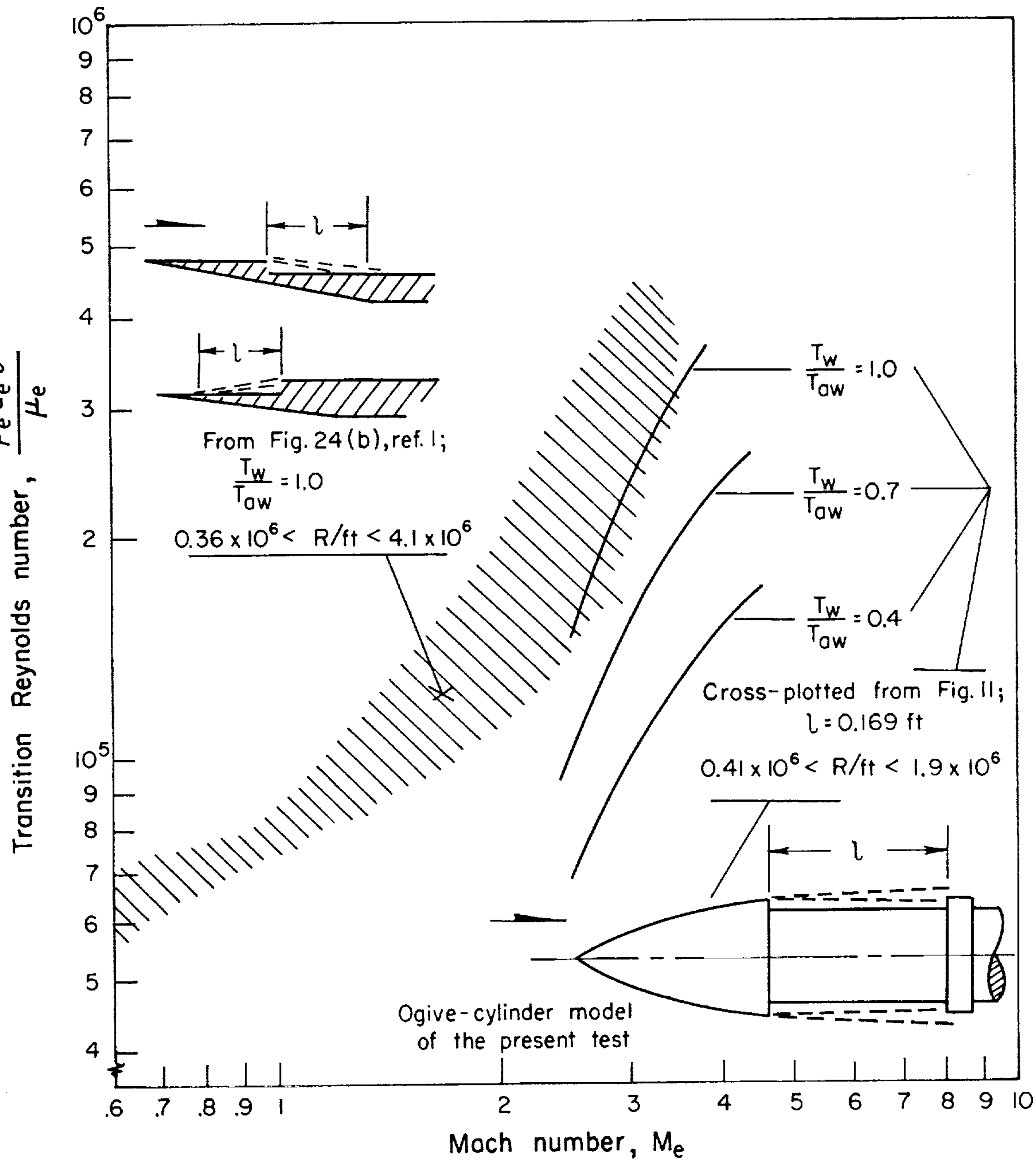

Figure 12.- Comparison of axially symmetric flow results for the present tests with the two-dimensional flow results of reference 1.